Analysis of the Systematic Errors in the Positions of BATSE Catalog Bursts

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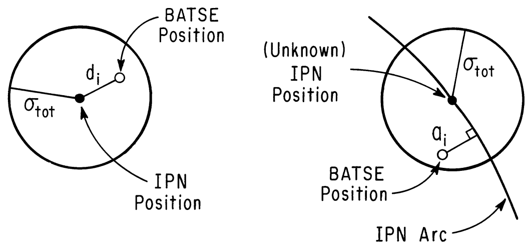
We analyze the systematic errors in the positions of bursts in the BATSE 1B, 2B and 3B catalogs, using a likelihood approach. We use the BATSE data in conjunction with 196 single IPN arcs. We assume circular Gaussian errors, and that the total error is the sum in quadrature of the systematic error $\sigma_{\rm sys}$ and statistical error $\sigma_{\rm stat}$, as prescribed by the BATSE catalog. We find that the 3B burst positions are inconsistent with the value $\sigma_{\rm sys} = 1.6^\circ$ stated in the BATSE 3B catalog.

INTRODUCTION

The stated systematic error in the BATSE 3B catalog (1) burst locations is $\sigma_{\rm sys} = 1.6^\circ$. This value was estimated by taking the RMS deviation of BATSE positions from known positions of 36 bursts, determined by the IPN, WATCH, and COMPTEL (2). Unfortunately, many of these same known positions were used to calibrate the BATSE burst location software, i.e., as a guide in determining what effects to include in the burst location algorithm. In order to calibrate properly the BATSE burst position errors, an independent set of burst locations is needed. Such a set exists, in the form of 196 bursts for which single IPN arcs exist (3). In this paper we analyze the systematic errors in the positions of bursts in the BATSE 1B, 2B and 3B catalogs using these 196 bursts. Our analysis is based upon the likelihood approach.

ANALYSIS

We assume that the systematic error $\sigma_{\rm sys}$ and statistical error $\sigma_{\rm stat}$ in position are circular Gaussians, to be added in quadrature, as prescribed by the BATSE catalog. The circular approximation should be good, since roughly $2/3 - 3/4$ of all BATSE bursts have χ^2 positional contours that are nearly circular (2), and the bursts with IPN arcs tend to be those with larger fluences. We further assume that the sky is flat (i.e., that the size of the total error in the BATSE burst position is not too large), and that the IPN arcs have zero width. The former is a good approximation, since the largest BATSE $\sigma_{\rm tot} \approx 12^\circ \ll 90^\circ$ among the bursts with IPN arcs. The latter is a good approximation since the characteristic width of the 3-σ contours of the IPN arcs is a few arcminutes, which is much less than the smallest BATSE $\sigma_{\rm tot} \approx 1^\circ$.



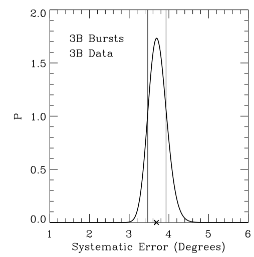


Figure 1. Configurations for a burst with a known position (left diagram) and for a burst with a single IPN arc (right diagram).

Figure 2. Probability density as a function of $\sigma_{\rm sys}$ for the ML constant $\sigma_{\rm sys}$ model. The vertical lines show the ± 1-σ interval.

The likelihood function for bursts with known positions (e.g., two intersecting IPN arcs) is given by

$$\mathcal{L}(\sigma_{\rm sys}) = \prod_{i=1}^{N} L_i \equiv \prod_{i=1}^{N} \frac{1}{2\pi\mu_i^2} \exp\left(-\frac{1}{2}\frac{d_i^2}{\mu_i^2}\right) \ , \tag{1}$$

whereas the likelihood function for bursts with single IPN arcs is given by

$$\mathcal{L}(\sigma_{\rm sys}) = \prod_{i=1}^{N_{\rm arc}} L_i \equiv \prod_{i=1}^{N_{\rm arc}} \frac{1}{\sqrt{2\pi}\mu_i} \exp\left(-\frac{1}{2}\frac{a_i^2}{\mu_i^2}\right) \ . \tag{2}$$

Here, d_i is the deviation of the BATSE position from the known position, a_i is the perpendicular deviation of the BATSE position from the IPN arc (see Figure 1), and $\mu_i = 0.43\sigma_{\rm tot} = 0.43(\sigma_{\rm sys}^2 + \sigma_{\rm stat}^2)^{1/2}$.

The likelihood function $\mathcal{L}(\sigma_{\rm sys})$ allows exploration of any model that we may have for $\sigma_{\rm sys}$. Here we focus on three models: (1) $\sigma_{\rm sys}$ = a constant, (2) $\sigma_{\rm sys} = A(S/10^{-5}\ {\rm erg\ cm^{-2}})^\alpha$, and (3) $\sigma_{\rm sys} = A(\sigma_{\rm stat}/1^\circ)^\alpha$. The first model has one free parameter ($\sigma_{\rm sys}$); the second and third models have two free parameters (scale factor A and power law index α).

RESULTS

Fitting the constant $\sigma_{\rm sys}$ model to the 18 BATSE 3B bursts with IPN positions, we find a maximum likelihood (ML) value $\sigma_{\rm sys}^{\rm ML} = 1.85^{\circ}{}^{+0.28^\circ}_{-0.22^\circ}$. This is consistent with the value of 1.6° quoted in the BATSE 3B catalog (1), which was found using these bursts and some others.

Fitting the constant $\sigma_{\rm sys}$ model to the 196 BATSE 3B bursts with IPN arcs, we find a ML value $\sigma_{\rm sys}^{\rm ML} = 3.7^{\circ}{}^{+0.24^\circ}_{-0.22^\circ}$. This is inconsistent (at the 10σ level!)

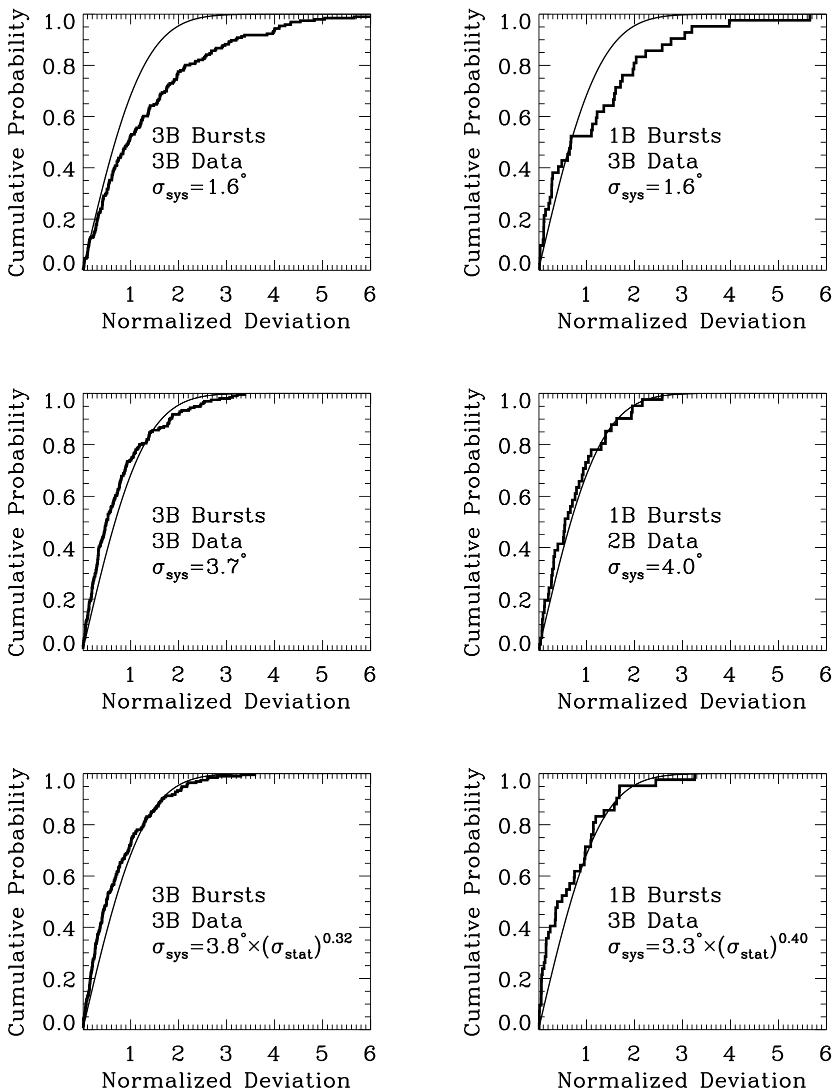


Figure 3. Comparison of expected and observed cumulative distributions of the normalized deviation $D = |a_i/\sigma^i_{\rm tot}|$ for the burst samples and data as labeled, assuming the ML models of $\sigma_{\rm sys}$ as labeled.

with the value of 1.6° quoted in the BATSE 3B catalog, as shown by the probability distribution in $\sigma_{\rm sys}$ (see Figure 2) and comparison of the expected and observed distribution of normalized deviations $D = |a_i/\sigma^i_{\rm tot}|$ assuming $\sigma_{\rm sys} = 1.6°$ (see Figure 3).

Fitting the second model, in which $\sigma_{\rm sys} = A(S/10^{-5}\ {\rm erg\ cm^{-2}})^{\alpha}$, we find

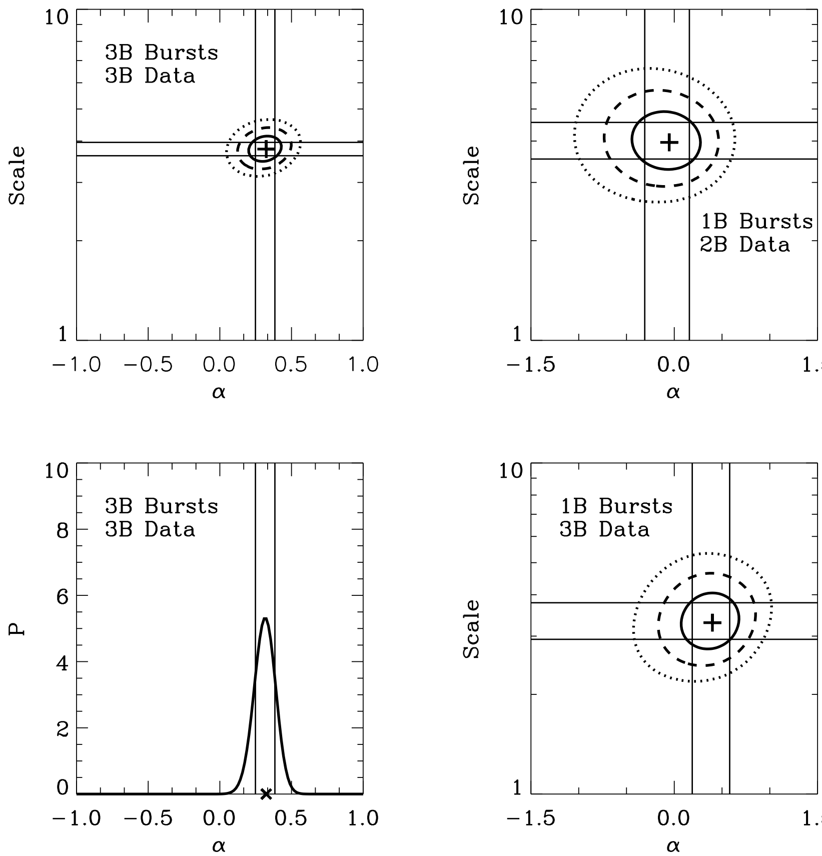


Figure 4. Upper left-hand and lower and upper right-hand panels: 1-σ, 2-σ, and 3-σ contours in the (A, α)-plane for the burst samples and data as labeled, assuming the $\sigma_{\rm stat}$-dependent model. Lower left-hand panel: same as Figure 2, except for the $\sigma_{\rm stat}$-dependent model.

ML values $A_{\rm ML} = 3.8 \pm 0.3$ and $\alpha_{\rm ML} = -0.18^{+0.06}_{-0.05}$. The probability $P(\alpha \geq 0) = 1.6 \times 10^{-3}$, showing that the data prefer the power-law model over the ML model with constant $\sigma_{\rm sys} = 3.7°$.

Fitting the third model, in which $\sigma_{\rm sys} = A\sigma_{\rm stat}^{\alpha}$, we find ML values $A_{\rm ML} = 3.8 \pm 0.2$ and $\alpha_{\rm ML} = 0.32^{+0.06}_{-0.08}$ (see Figure 4). The probability $P(\alpha \leq 0) = 4.7 \times 10^{-5}$, showing that the data strongly prefer the power-law model over the ML model with constant $\sigma_{\rm sys} = 3.7°$.

These results imply that $\sigma_{\rm sys}$ is strongly correlated with S and $\sigma_{\rm stat}$. For example, $\sigma_{\rm sys}(\sigma_{\rm stat} = 0.1°) = 2°$ while $\sigma_{\rm sys}(\sigma_{\rm stat} = 10°) = 8°$. This is il-

lustrated in Figure 5, which shows the ML S-dependent and $\sigma_{\rm stat}$-dependent models.

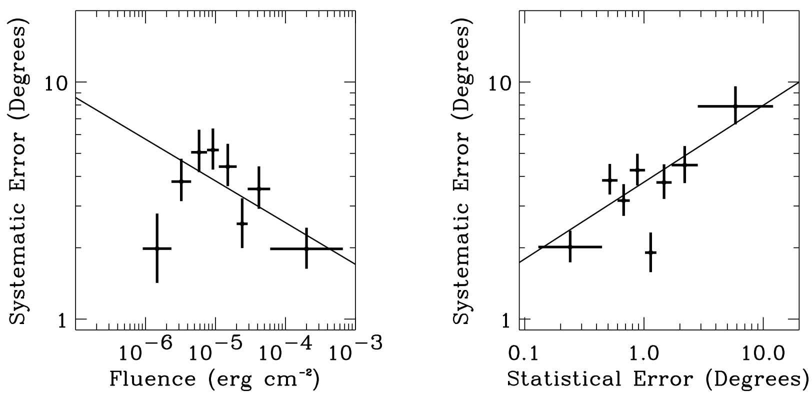


Figure 5. Left-hand panel: The ML S-dependent model. Right-hand panel: The ML $\sigma_{\rm stat}$-dependent model. The points are *not* data points, but rather are the ML *constant* $\sigma_{\rm sys}$ model for the given interval in S or $\sigma_{\rm stat}$.

It is also interesting to examine the character of $\sigma_{\rm sys}$ for subsets of the 3B catalog, in particular the 1B sample of bursts in which evidence for repeating was found. Fitting the three models to the "old" 1B positions, we find $\sigma_{\rm sys} = 4.0°$ for the ML constant $\sigma_{\rm sys}$ model, and that the data do not request a more complicated model(see Figures 3 and 4). In contrast, fitting the 3B positions for the 1B sample of bursts, we find that the data request the $\sigma_{\rm stat}$-dependent model at the 95% confidence level [e.g., $P(\alpha \leq 0) = 1.6 \times 10^{-2}$] (again see Figures 3 and 4).

These results imply that for the 1B sample of bursts, the new (3B) $\sigma_{\rm sys}$'s are smaller than the old (1B) ones for bursts with $S > 4 \times 10^{-6}$ erg cm^{-2} or with $\sigma_{\rm stat} < 1.6°$. However, for the $\approx 80\%$ of bursts with lower fluences or larger $\sigma_{\rm stat}$'s, they imply that the new $\sigma_{\rm sys}$'s are larger than the old ones.

We are grateful to Kevin Hurley for providing us with the 3rd catalog of IPN arcs, without which this analysis would not have been possible. We also wish to thank Geoff Pendleton and Michael Briggs for discussing BATSE burst location issues with us.

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